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Metamaterials and Transformation Optics

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14. ABSTRACT

One of the chief interests during visits to USA was the new concepts in cloaking the theory for which was developed at Imperial College London and whose implementation was made first in Duke University at microwave frequencies, and secondly at UCB for optical frequencies. It is evident from the above that there has been considerable exchange of ideas between the US groups and the College of London stimulating 2 Physical Review Letters, one Science paper, and one Nature Materials paper.. This continues, and further exchange of personnel is planned for 2010. Several joint projects are under way including a review co-authored by David Smith and John Pendry.

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Metamaterials and transformation optics

report on activities February 2009 – January 2010

JB Pendry

During the first year of activities there were 4 separate visits to the USA:

- Visit to Professor David Smith at Duke University and WPAFB: Monday 2 February to Saturday 28 February 2009
- Attending the DARPA kickoff meeting at Duke University: Sunday 26 to Thursday 30 July 2009
- Visit to Professor Vlad Shalaev at Purdue, Professor David Smith at Duke, WPAFB, and Sandia National Laboratories: Monday 16 to Thursday 26 November 2009
- Attend the Physics and Quantum Electronics conference with sessions organised by Vlad Shalaev and myself, and visit to Professor Xiang Zhang, UCB Saturday 2 January to Saturday 16 January 2010 snowbird

This makes up the two months agreed time in the USA.

One of the chief interests during these visits was the new concepts in cloaking the theory for which was developed in my group in London and whose implementation was made first in Duke University at microwave frequencies, and secondly at UCB for optical frequencies

Cloaking has been a topic of my collaboration with US scientists for the past few years. The original concept faced two challenges: to extend the operating frequency to the optical and to make a broad band device. Jensen Li my post doc and I investigated the topology of cloaking. There are three routes to invisibility. In effect the cloak alters the *shape* and *conductivity* of an object. Depending on the configuration the object appears as either a perfectly conducting *point*, or a *line*, or *sheet*.

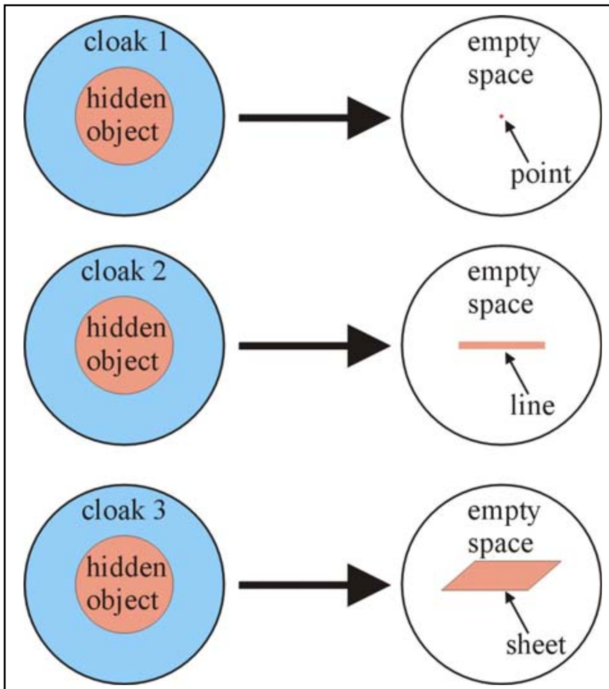

Fig. 1. A cloak functions by making the hidden object appear very small and this can happen in three topologically distinct ways: crushed to a point a line or an infinitely thin sheet

The first two methods require materials with extreme values of the refractive index but are perfectly invisible. The third method gives the appearance of a thin mirror, but requires modest values of the refractive index within the cloak, and we can hide the mirror by placing it upon another mirror or

ground plane. This work appeared just before my visits to the USA

Hiding Under the Carpet: a New Strategy for Cloaking, Jensen Li & JB Pendry, *Physical Review Letters* **101** 203901 (2008).

The ideal carpet cloak, like all cloaks, required equal values of ε and μ so that the correct refractive index profile is achieved whilst keeping the impedance matched. As a compromise impedance matching can be neglected provided that all interfaces are smoothly varying and the refractive index profile achieved entirely by varying ε. There is one caveat: the material of the cloak cannot be anisotropic as in the original cloak, otherwise it would cloak only one polarisation.

This paper uses the original cloaking prescription, except that implementation no longer requires the 'split ring' structures and the required parameters can easily be achieved at optical frequencies:

….. the cloak is a tunnel $4\mu\text{m}$ by $1.5\mu\text{m}$ … and is defined relative to silica (SiO_2) of permittivity $\varepsilon_{ref} = 2.25$. In this case, the permittivity of the cloak varies in the range $1.5 < \varepsilon < 4.4$. This range can be obtained etching or drilling sub-wavelength holes of different sizes along a direction parallel to the hidden tunnel, in a high dielectric, e.g., Si. The inner surface of the cloak is coated by a highly reflective metal such as silver or aluminium. …..

To achieve an isotropic cloak we optimise the refractive index profile for isotropy by developing the theory of quasi-conformal mapping

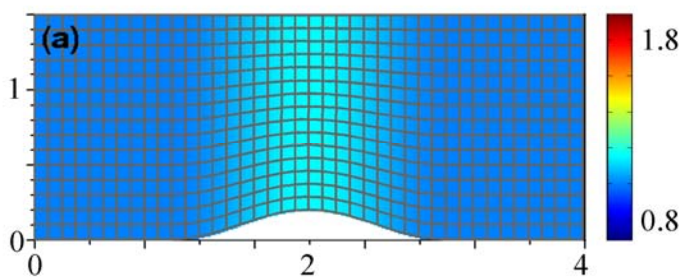

Fig. 2 A cloaking cavity opened by compressing the *y*- coordinate to give anisotropic cells. The colour bar shows the profile in n^2. The *x* and *y* scales are given in μm.

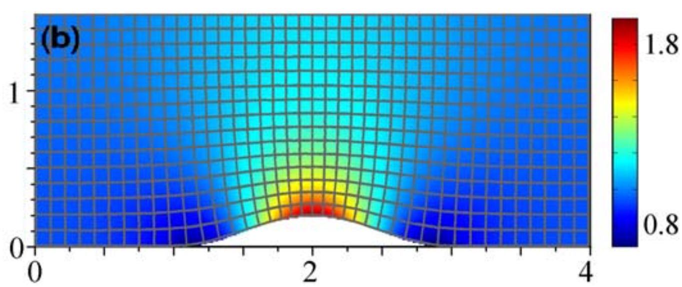

Fig. 3. Quasiconformal grid gives almost isotropic cells, but a greater index contrast.

Duke implementation of the new cloak

Experimental realisation of the cloak was first made by the Duke team:

Broadband Ground-Plane Cloak, R. Liu, C. Ji, J. J. Mock, J. Y. Chin, T. J. Cui, D.R. Smith, *Science* **323** 366 (2009)

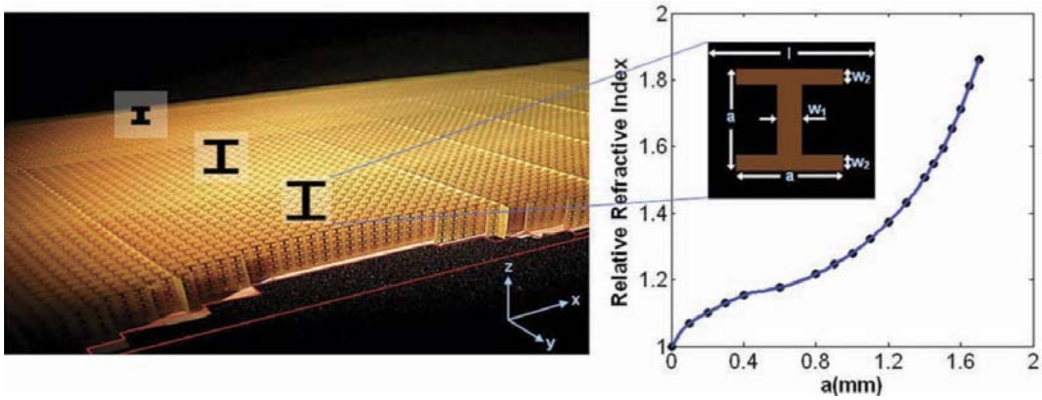

Fig.4. Design of the non-resonant elements and relation between the unit cell geometry and effective index, n. Dimensions of the metamaterial unit cells are: $\ell = 2\text{mm}$, $w_1 = 0.3\text{mm}$, $w_1 = 0.2\text{mm}$, and $0 < a < 1.2\text{mm}$.

The cloak is fabricated on copper-clad printed circuit board with FR4 substrate. The completed sample is $500 \times 106\text{mm}$ with a height of 10mm. The centre region, $250 \times 96\text{mm}$, corresponds to the transformed cloaking region.

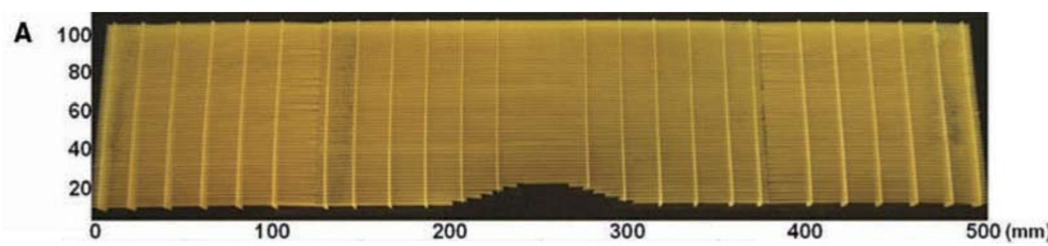

Fig. 5. Photograph of the fabricated metamaterial sample.

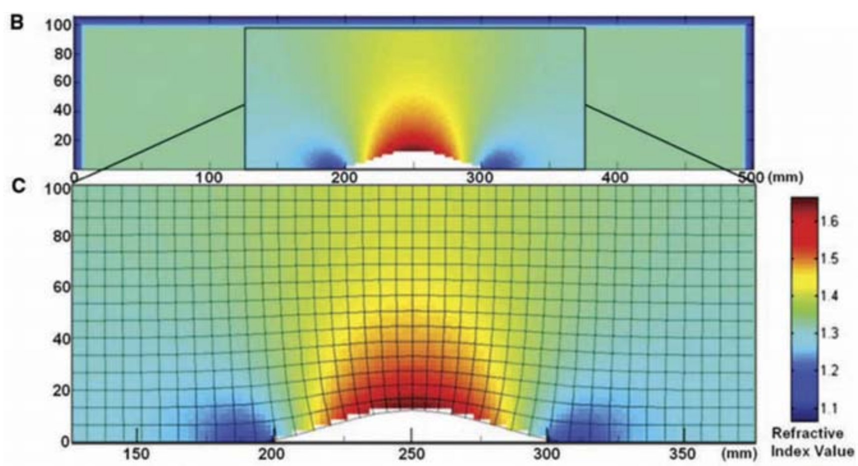

Fig. 6. Metamaterial refractive index distribution. The cloak is shown within the box outlined in black. The surrounding material is the higher index embedding region. (C) Expanded view of cloaking region.

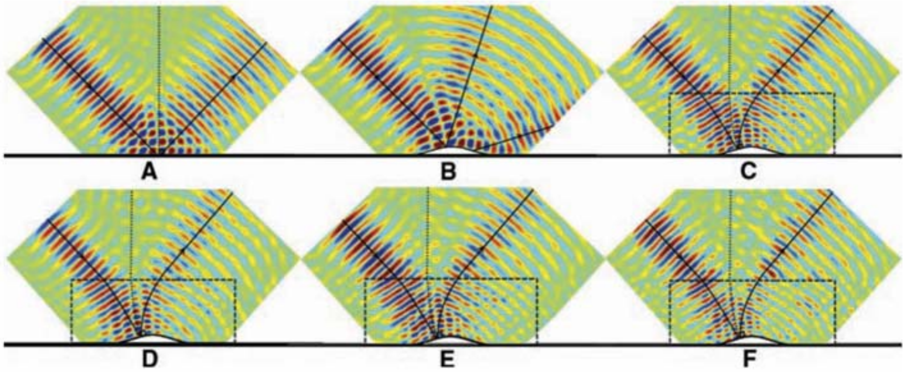

Fig. 7. Experimental field mapping (E-field) for a collimated beam incident on the (A) ground plane at 14 GHz; (B) perturbation at 14 GHz (no cloak); (C) cloaked perturbation at 14 GHz; (D) cloaked perturbation at 13 GHz; (E) cloaked perturbation at 15 GHz (F) the cloaked perturbation at 16 GHz.

UCB implementation of the new cloak at optical frequencies

An optical cloak that uses dielectrics, Jason Valentine, Jensen Li, Thomas Zentgraf, Guy Bartal & Xiang Zhang, *Nature Materials* **8** 568 (2009)

My post doc, Jensen Li, moved on to Xiang Zhang's group at UCB shortly after our 'carpet cloak' theory was published and there he participated in the first experimental demonstration of optical cloaking deemed 'carpet cloaking'. The optical cloak is designed using quasi-conformal mapping to conceal an object that is placed under a curved reflecting surface by imitating the reflection of a flat surface. The cloak consists only of isotropic dielectric materials, which enables broadband and low-loss invisibility at a wavelength range of 1400 - 1800 nm.

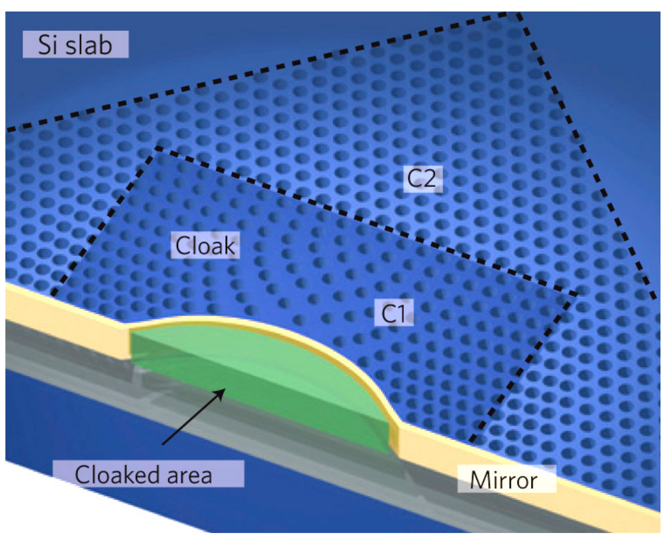

Fig. 8. Schematic diagram of a fabricated carpet cloak showing the different regions, where C1 is the gradient index cloak and C2 is a uniform index background. The cloak is fabricated in a SOI wafer where the Si slab serves as a 2D waveguide.

The cloaked region (marked with green) resides below the reflecting bump (carpet). and can conceal any arbitrary object. The cloak will transform the shape of the bump back into a virtually flat object.

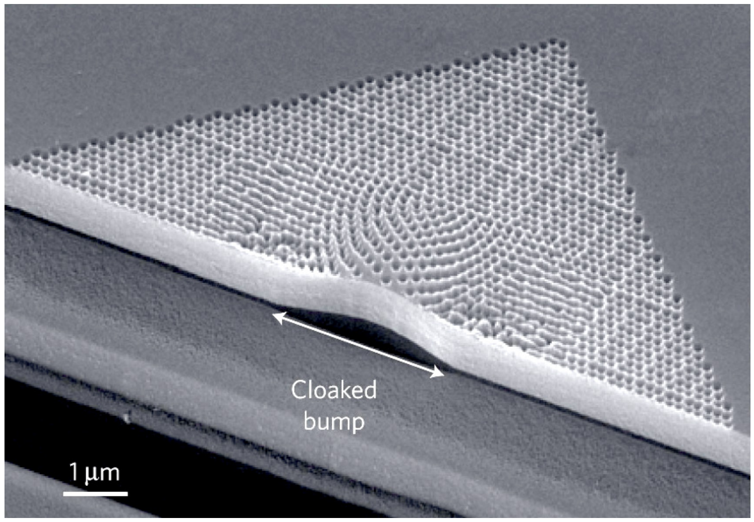

Fig. 9. Scanning electron microscope image of a fabricated carpet cloak. The width and depth of the cloaked bump are 3.8 µm & 400 µm , respectively.

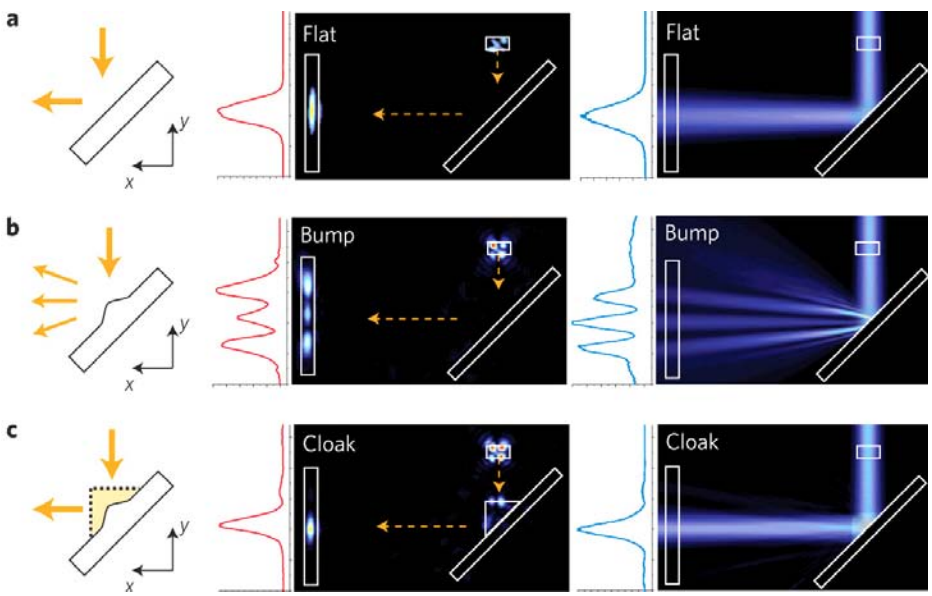

Fig. 10. The optical cloaking experiments (**a**) Gaussian beam reflected from a flat surface (**b**) a curved (without a cloak) surface (**c**). and the same curved reflecting surface with a cloak Left column: the schematic diagrams; right column: optical microscope images red curves: experimental intensity profile. blue curves: computer simulations

Purdue implementation of a 'conventional' cloak at optical frequencies

A visible frequency cloak, I.I. Smolyaninov, V.N. Smolyaninova, A.V. Kildishev, & V.M. Shalaev, *Physical Review Letters*, **102**, 213901 (2009)

In this work cloaking is achieved by guiding light around the hidden region. This can be achieved using a smoothly varying refractive index – difficult in practice. A waveguide has an effective refractive index determined by its height. Varying the height tunes the refractive index – a much simpler procedure.

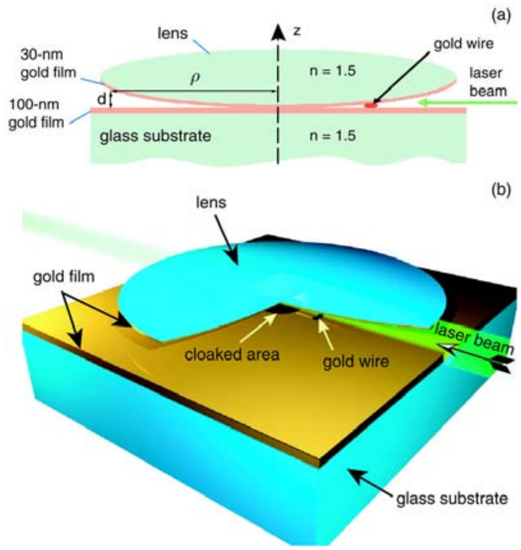

Fig. 11. The Purdue cloak comprising a gold coated lens touching a gold coated flat plate to form a 2D waveguide with a varying cross section and therefore varying effective refractive index. It happens that the refractive index profile is almost exactly what is required by cloaking theory

It is evident from the above that there has been considerable exchange of ideas between the US groups and my group in London stimulating 2 Physical Review Letters, one Science paper, and one Nature Materials paper.. This continues, and further exchange of personnel is planned for 2010. Several joint projects are under way including a review co-authored by David Smith and myself

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1 February 2010